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Nanotechnology- An Emerging Hope in Dentistry

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The concept of nanotechnology has recently gathered interest in diagnostic and treatment implementation, although the visions described in various relations may sound heretical. Nanotechnology is expected to bring considerable advancements in the fields of restorative and preventive dentistry. Recent advancements have enabled nanoparticles to mimic biological agents closely. Opening ideas, findings, literature, research, tests, and trials can contribute to the success of nanotechnology over time. This systematic review highlights the recent work undertaken as a success of nanodentistry by the crown.
Keywords: Nano-composite, Nano-dentistry, Nano-endodotic sealers, Nano-targeted drug delivery , Nano TiO2-laser, Tissue engineering.

1. Introduction

Science is undergoing a significant evolution, advancing dental sciences into a new era of nanotechnology [1]. This affords us the opportunity to witness a pioneering development in technology, which is encountered rarely. This period of advances belongs to gene technology and nanotechnology, which is likely to touch every aspect of our life in the next few years [2].

First, Prof. Keric E. Dexler coined the term NANO meaning dwarf [3]. While nanotechnology was highlighted by Richard Feynman, a physicist at the American Physical Society, California Institute of Technology, Pasadena, CA [4].

Nanotechnology and its enigmatic role in dentistry has revolutionized the use of particles with small, minute dimensions in the sphere of drugs, anesthesia, sealers, restorative materials, robots, local drug delivery, and nano-robots employed for the diagnosis of cancer and tumor typing. In 1998, James R. Baker, through his dendrimer's safer agent experiment, concluded that "these nanostructures can sneak DNA into cells while avoiding triggering an immune response. DNA is released to the nucleus where it becomes part of the cell's genome," and this technology has since been used in mammalian cell types as well [5].

After this, various researches in the field of nanotechnology made it the array of hope for future advanced medical and dental sciences. Nanotechnology, an emerging field, besides revolutionizing the era, has also unraveled advanced and improvised oral diagnostic and/or interventional treatment methods. It is appropriate to entitle it as a separate field with enormous potential for qualitative outcomes in relation to dental materials, medicine, methodology, and treatment [6]. Before incorporating any field into the treatment regimen, it is essential to consider human safety, biocompatibility, public acceptance, and legal regulations. In this article, the role that nanotechnology can play in the field of dentistry, as a boon to humanity, is revisited.

Defining the need and role of Nanotechnology in dentistry is a pleasure to give a miracle band in the hands of an engineer and artist, i.e., a dentist.

Well among many fields of dentistry, nanotechnology had already been proven separate indispensable entity:

- Local anesthesia
- Nano needles
- Endodontic sealers
- Dental composite and restorations / Nano Composites
- Oral Hygiene Maintenance / Dentifrobots
- Bone Defects
- Local Drug Delivery
- Early cancer detection
- Tissue Regeneration and fibronectin
- Laser Application
- Dental Implants
- Orthodontic Arch Wires
- Gingival and Periodontal Diseases

- Surgical Field

2. Methodology

Research Design: This study adopts a systematic literature review (SLR) approach to comprehensively analyze and synthesize the role of nanotechnology in dentistry. The objective is to evaluate existing research, identify technological advancements, assess clinical applications, and discuss future prospects and challenges associated with nanotechnology in dental sciences.

Inclusion and Exclusion Criteria: To ensure a focused and relevant review, specific inclusion and exclusion criteria were applied. The inclusion criteria encompassed studies published in peer-reviewed journals between 2000 and 2024 that discussed the application of nanotechnology in various branches of dentistry such as restorative dentistry, periodontics, endodontics, orthodontics, prosthodontics, and oral cancer detection. Additionally, research focusing on nanotechnology-based drug delivery, tissue regeneration, and dental implant advancements was included. Studies that explored biocompatibility, human safety, and the clinical efficacy of nano-based materials were also considered. Eligible sources included original research articles, systematic reviews, meta-analyses, and randomized controlled trials. Studies that were not related to dental sciences or nanotechnology, lacked sufficient clinical evidence or laboratory validation, or were published in languages other than English without a reliable translation were excluded. Duplicate studies and conference abstracts with insufficient data were also excluded from the review.

Literature Search Strategy: A comprehensive and systematic search was conducted using electronic databases such as PubMed, Scopus, Web of Science, Google Scholar, and the Cochrane Library. To refine the search results, a combination of Medical Subject Headings (MeSH) and free-text terms were used, including keywords such as “Nanotechnology in dentistry,” “Nanoparticles in oral health,” “Nano-based drug delivery in dentistry,” “Nanodentistry and its applications,” and similar terms. Boolean operators such as AND, OR, and NOT were utilized to fine-tune the search strategy. To ensure that no relevant studies were missed, manual searches of the reference lists in selected articles were also conducted.

Study Selection Process: The study selection process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and transparency. The selection process involved three stages: initial screening of titles and abstracts to remove irrelevant studies, a full-text review of potentially relevant articles to assess their eligibility based on the inclusion and exclusion criteria, and resolution of discrepancies between reviewers through discussion and consensus [Figure 1].

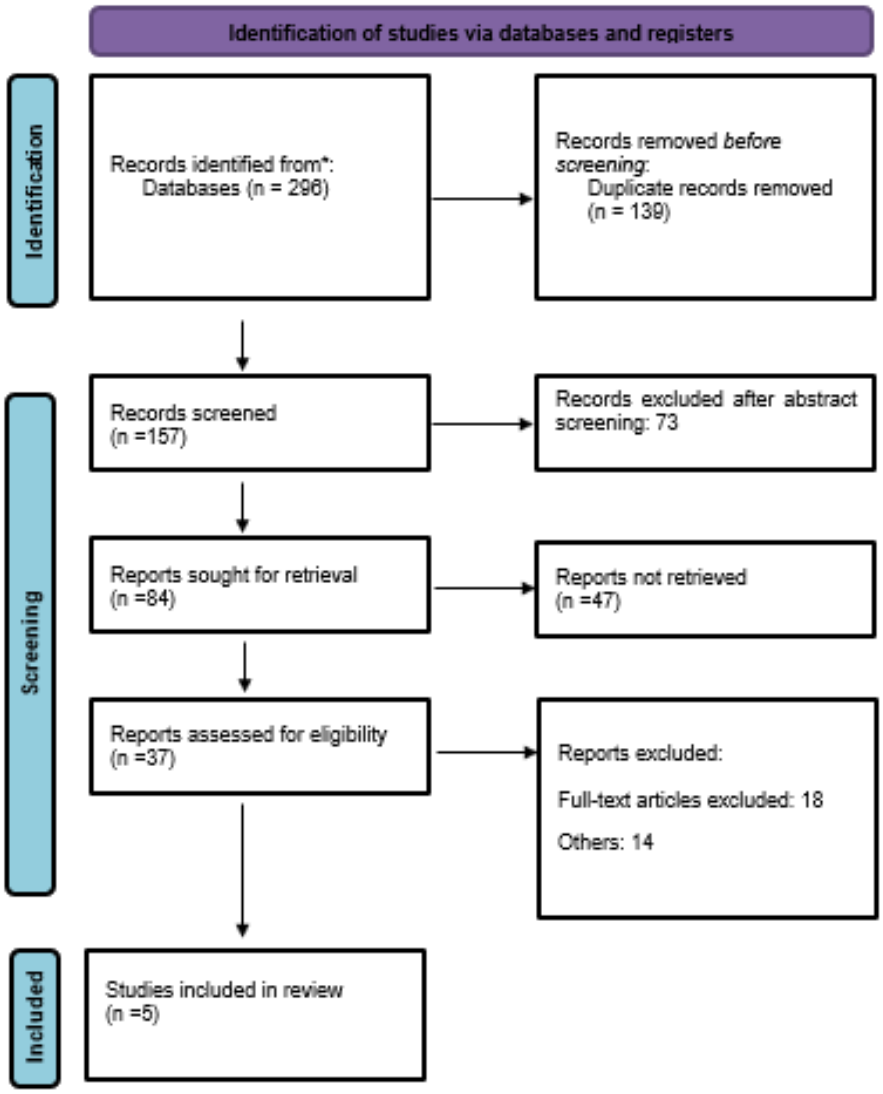

Figure 1: Prisma Flowchart of the study

A standardized data extraction form was developed to collect and organize relevant information from the selected studies. The extracted data included details such as the study title, author(s), year of publication, objective, scope, type of nanotechnology application in dentistry, methodological approach, key findings, outcomes, limitations, and future directions. The extracted data was then synthesized using qualitative analysis to categorize and analyze findings based on different applications of nanotechnology in dentistry. Descriptive and thematic analyses were used to identify emerging trends, advancements, and challenges in the application of nanotechnology to dental sciences.

Data Extraction and Synthesis: To ensure the reliability and validity of the findings, the quality

of the included studies was assessed using established tools. The Cochrane Risk of Bias Tool was applied for randomized controlled trials, while the Newcastle-Ottawa Scale (NOS) was used for observational and cohort studies. Additionally, the Joanna Briggs Institute (JBI) Critical Appraisal Tools were used to assess the quality of systematic reviews and meta-analyses. Each study was independently evaluated by two reviewers, and any discrepancies were resolved through consensus.

Quality Assessment and Risk of Bias: Since this study is a systematic literature review, it did not involve direct interaction with human or animal subjects, and therefore, ethical approval was not required. However, care was taken to ensure that all included studies adhered to appropriate ethical guidelines.

Despite the rigorous methodology employed, the study has certain limitations. Potential publication bias may exist due to the inclusion of only peer-reviewed studies. Moreover, the exclusion of non-English studies may have resulted in the omission of relevant information. Additionally, given the rapidly evolving nature of nanotechnology, recent advancements that are yet to be published may not be captured in this review.

3. Review

This literature review examines five key studies that explore the applications of nanotechnology in dentistry. Malik and Waheed (2023) conducted a systematic review published in the Dentistry Journal that highlights the emerging applications of nanotechnology in restorative dentistry, drug delivery, and diagnostics. Their study discusses how nanomaterials can improve the longevity and biocompatibility of dental materials [7]. Similarly, Ingle and Gopal (2011) published an article in Dentist that critically evaluates whether nanodentistry is merely a theoretical concept or has practical applications in clinical dentistry [8]. This literature review explores potential advancements and ethical concerns associated with nanotechnology in dental practice.

Patil, Mehta, and Guvva (2008), in their narrative review published in the Journal of Indian Society of Periodontology, focus on the future implications of nanotechnology in medicine and dentistry [9]. Their work emphasizes the potential role of nanotechnology in tissue regeneration, drug delivery, and biofilm control. In contrast, Kochan et al. (2022) conducted an experimental study published in Applied Sciences, which explores how theoretical concepts of nanodentistry have been transformed into clinical practice through the introduction of nano-impression materials, nano-drug delivery systems, and nanocomposites [10].

Lastly, Wadhawan et al. (2024) published a systematic review in Frontiers in Health Informatics that evaluates the applications of nanotechnology in oral and maxillofacial surgery. Their study highlights improvements in tissue healing, precision surgery, and targeted drug delivery. Collectively, these studies demonstrate the transformative potential of nanotechnology in various fields of dentistry, paving the way for future advancements and clinical applications [11]. [Table 1]

Table 1 : Summary of Literature Review on Nanotechnology in Dentistry

S. No.	Author(s) and Year	Title	Journal	Research Methodology/Approach	Key Focus/Findings
1	Malik S and Waheed Y (2023) [7]	Emerging applications of nanotechnology in dentistry	Dentistry Journal	Systematic Review	This study highlights the emerging applications of nanotechnology in restorative dentistry, drug delivery, and diagnostics. It explores how nanomaterials improve the longevity and biocompatibility of dental materials.
2	Ingle E and Gopal KS (2011) [8]	Nanodentistry: A Hype or Hope	Dentist	Literature Review	The article critically evaluates whether nanodentistry is merely a theoretical concept or has practical applications in clinical dentistry. It discusses potential advancements and ethical concerns.
3	Patil M, Mehta DS and Guvva S (2008) [9]	Future Impact of Nanotechnology on Medicine and Dentistry	Journal of Indian Society of Periodontology	Narrative Review	This study focuses on the future implications of nanotechnology in medicine and dentistry, emphasizing its role in tissue regeneration, drug delivery, and biofilm control.
4	Kochan O, Boitsaniuk S, Levkiv M, Przystupa K, Manashchuk N, Pohoretska K and Patskan L (2022) [10]	Emergence of Nano-Dentistry as a Reality of Contemporary Dentistry	Applied Sciences	Experimental Study	This study explores the transformation of theoretical nanodentistry into clinical practice by introducing nano-impression materials, nano-drug delivery systems, and nanocomposites.
5	Wadhawan R, Chauhan A, Jadon G, Dubey S, Pathak A and Singh V (2024) [11]	Tiny Innovations, Big Impact: Role of Nanotechnology in Oral and Maxillofacial Surgery: A Systematic Review	Frontiers in Health Informatics	Systematic Review	This systematic review evaluates the applications of nanotechnology in oral and maxillofacial surgery, including improved tissue healing, precision surgery, and targeted drug delivery.

4. Discussion

Local Anesthesia and Nano Needles: With the use of nanotechnology, local anesthesia is

induced by means of a colloidal suspension incorporated with millions of nano-sized active analgesics. As the solution comes in contact with the tooth surface or gingiva, it reaches the pulp through layers of gingival epithelium, resulting in a temporary and reversible shutdown of all the pain receptors in the area of interest [12]. Another factor is that it can be controlled remotely by the dentist via a computer, allowing for reversible action and control of the mean time fraction as well. Nano needles perform surgeries that are just a few billionths of a meter and are also aided in oncology research for targeted drug delivery along with Mohs surgery [13].

Endodontic Sealer: The nano-sized particles encourage the easy delivery of materials resulting in excellent seal and dimensional stability, even in cases with complex and irregular dentinal surfaces, and exhibit excellent biocompatibility and antimicrobial properties [14].

Dental Composite and Restorations / Nano Composite: The incorporation of nanoparticles in composites enables a greater amount of fillers, resulting in a high degree of resistance and strength, which is easy to manipulate according to the required shape [15].

Oral Hygiene Maintenance / Dentifrobot: The use of nanotechnology in patrolling supragingival and subgingival surfaces aids the metabolism of trapped organic matter into harmless vapors. This enables the destruction of specific target microorganisms anywhere in the oral cavity without interfering with the normal oral microflora. Use of a mouthwash or toothpaste that delivers nanorobotic structures results in the release of organic compounds into odorless structures and the continuous cleaning of calculus—a hope that needs to be investigated for biocompatibility. These dentifrobot models, as proposed, which are nearly invisible (1 to 10 μm), will work as fully mechanical devices. Furthermore, they are employed to recognize and destroy pathogenic bacteria in plaque and other regions, but they do not affect approximately 500 harmless species in normal flora and thus contribute to the formation of a healthy ecosystem, as per reported data [16].

Dental Hypersensitivity: Dentinal tubules of a sensitive tooth have twice the diameter and eight times the surface density compared to a normal tooth. With the use of nanotechnology, selective occluding of the dentinal tubules in a fraction of minutes results in permanent cure and immediate relief to the patient [17].

Impression Material: Unique siloxane impression material with nanofillers is integrated into vinyl-polysiloxanes, resulting in better flow and excellent hydrophilic properties, providing enhanced precision details [18].

Bone Defects: Nanophase hydroxyapatite and carbon are two materials used for bone defect treatments and show superior results in osteoblastic adhesions compared to traditional ones [19].

Local Drug Delivery: Local drug delivery minimizes drug-induced side effects by selectively depositing drugs in the area of interest. This drug delivery system has been developed in which triclosan loaded with nanoparticles has an improved role in treating periodontal and gingival diseases. One example of such a local drug delivery system consists of tetracycline fibers and has been widely used to treat periodontal conditions [20].

Tissue Regeneration and Fibronectin: Newer scaffold materials are being introduced for tissue regeneration. These scaffolds are blueprints of nanofibers (biodegradable collagen type I),

acting as precursors for the formation of a nanofiber mesh. This is responsible for the growth of cells during tissue engineering. Puramatrix and natural silk-based nanomaterials have followed the consideration of human safety and biocompatibility [21].

Laser Application: Nanoparticles of titanium dioxide (TiO_2) coupled with laser irradiation on the human skin surface exhibit shock wave effects, microabrasion, and stimulation of collagen production when irradiated with laser pulses. Such remarkable properties are also utilized in various procedures such as soft tissue incision, depigmentation of gingiva without anesthesia, with profound results [22].

Dental Implants: Osteoblast proliferation induced through nano-sized particles on implant surfaces is a robust nanoequipment. Roughening of the implant surface at the nanoscale level improves the cellular response, resulting in enhanced osteoblast adhesion [23].

Detection of Oral Cancer: Nano electromechanical systems convert biochemical signals into electrical signals that are diagnostic for precancerous and cancerous hotspots. Treatment modalities in this category include nanomaterials for targeted drug therapy, brachytherapy drug delivery across the blood-brain barrier that offers more effective treatment for brain tumors, Alzheimer's disease, and nanovectors for gene therapy. To detect cancer at its earliest stages, this technology enables the detection of molecular changes even when they occur in a small percentage of cells. The potential of nanostructures to analyze single cells aids in typing tumors and detecting secondary mutations in malignancy [24].

Orthodontic Arch Wires: Orthodontic nanorobots (still in research) directly manipulate oral tissues, causing very little discomfort, saving time, and resulting in hassle-free orthodontic treatment [25]. Orthodontic nanorobots will be able to directly manipulate all of the periodontal tissues, including gingival, periodontal ligament, cement, and alveolar bone. Also, they will correct, rotate, or vertically reposition the teeth within a few hours in a pain-free manner, but this prospect needs further trials [26].

Gingival and Periodontal Diseases: Targeted nanoparticles destroy selective pathogens without hampering the natural flora in any part of the oral cavity [15]. Usage of this technology should enable many developments in the dental field, health sciences, materials science, biotechnology, electronic and computer technology, aviation, and space exploration for the welfare of mankind. Another prospect, enhancing periodontal therapy, indicates that targeted drug delivery with nanomaterials is possible for future use, referred to as Arestin, in which microspheres containing tetracycline are placed into periodontal pockets, and tetracycline is administered locally [27].

Surgical Field: Nano-sized stainless steel crystals have made it possible to develop nano-sized needles, tweezers, catheters, and other surgical instruments The use of such instrumentation results in good treatment outcomes through minimally invasive techniques like FNAC for diagnosis and interventional treatment as well [28].

Nanotechnology: Nanotechnology is an evolutionary science dealing with the physical, chemical, and biological properties of nanoparticles. It has already shown great promise in advanced diagnostics and targeted drug delivery. Dentistry is passing through a transformation phase into nanodentistry, which has also become a controversial issue due to insufficient evidence-based trials for potential hazards on human health and the environment [29].

5. Future Prospects:

In the future, preparing an autologous tooth with both mineral and cellular dental components by nanotechnology will be achievable in the dentist's office. Cosmetic alternatives to standard whitening techniques will definitely be provided by nanotubes, enabling the incorporation of durable sapphire and diamond particles into enamel crystals. However, pure sapphires and diamonds are fragile [30,31]. Their ultimate strength is augmented by the addition of carbon nanotubes. Sapphire will avail almost all colors from the color scale, and this feature provides a cosmetic alternative with hype. Employing nano diagnostic tools through saliva markers and flow cytometry is another important area that we, as authors, propose here. This will be a boon for the early detection of cancer or other saliva biomarkers predictive of the course of various pathoses such as hormones, infections, malignancies, etc.

The future of nanotechnology in dentistry is poised for transformation through the integration of Artificial Intelligence (AI), the Metaverse, Augmented Reality (AR), and Virtual Reality (VR), promising groundbreaking advancements in diagnosis, treatment, and education [32,33]. AI will enable real-time analysis of data from nano-devices, enhancing personalized treatment and predictive diagnostics, while nanosensors can monitor oral health biomarkers to detect early signs of disease. The Metaverse will create virtual dental ecosystems where researchers can simulate complex nano-procedures and experiment with nanomaterials in a risk-free environment [34,35]. AR will enhance the real-time visualization of nano-interventions, allowing for the precise placement of nano-implants and coatings during procedures, while VR will provide immersive simulations for practicing complex nano-dental techniques and tissue regeneration processes [36]. This convergence of technologies promises to revolutionize dental practice, ensuring minimally invasive, personalized, and highly accurate treatments while opening new avenues for research, training, and clinical applications in nanodentistry [37].

6. Conclusion:

Nanotechnology is a game changer when immediate success with both best predictive and prognostic outcomes needs to be accomplished. The availability of minimally invasive techniques and targeted drugs has already enhanced the treatment outcomes.

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